Terahertz Chirp Generation Using Frequency Stitched VCSELs for Increased LIDAR Resolution

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Abstract: We stitch the frequency chirps of two vertical-cavity surface-emitting lasers in a frequency-modulated imaging experiment at 1550nm. The effective frequency excursion is 1 THz, corresponding to a free-space axial resolution of 150 micrometers.

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The technique of optical frequency-modulated continuous-wave (FMCW) reflectometry has found applications in fields requiring high-resolution, non-invasive three-dimensional ranging and imaging. Examples include LIDAR [1], biomedical imaging [2] and integrated circuit profilometry [3], to name a few. The key component of an FMCW experiment is the swept-frequency (chirped) laser, since its performance directly affects important system metrics. Specifically, the axial resolution is given by $\delta d = c/2B$, where B is the total frequency excursion, and c is the speed of light [4]. The ranging depth is limited by the coherence of the optical wave and varies inversely with its instantaneous linewidth [5]. Mechanically tunable extended cavity lasers are commonly used in applications requiring axial resolutions of $<$10 μm, due to the wideband ($>$ 10 THz) tuning achievable with such systems. However, the low coherence associated with these devices limits the ranging depth to, at most, a few millimeters. Commercially available semiconductor lasers (SCLs), on the other hand, offer narrow linewidths corresponding to ranging depths of tens of centimeters to tens of meters, depending on the cavity design, and can be tuned by a modulation of the injection current. The drawback of SCL diodes is the comparatively small modehop-free tuning range of several hundred GHz. Therefore, a single SCL FMCW ranging experiment is limited in axial resolution to a few 100 μm. The key to extending the system's optical bandwidth, and therefore improving the axial resolution, is to concatenate multiple chirps over distinct but adjacent regions of the optical spectrum. This technique, stitching, has been used to improve the axial resolution three-fold in a distributed feedback laser (DFB) based system [4].

In the present work we demonstrate the stitching of two off-the-shelf vertical-cavity surface-emitting lasers (VCSELs) at 1550 nm. When compared to DFB lasers, VCSELs offer increased tunability, a faster chirp rate, as well as a significant cost reduction. Stitching enables the synthesis of a measurement with an enhanced axial resolution from

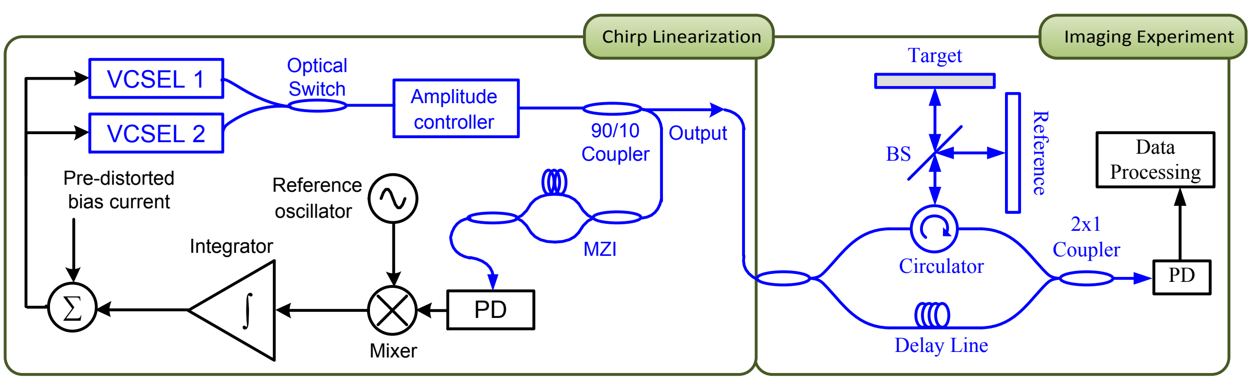

Fig. 1. System diagram. The feedback loop ensures chirp stability. A reference target is used to overcome starting frequency ambiguity. PD: Photodiode, BS: Beamsplitter.

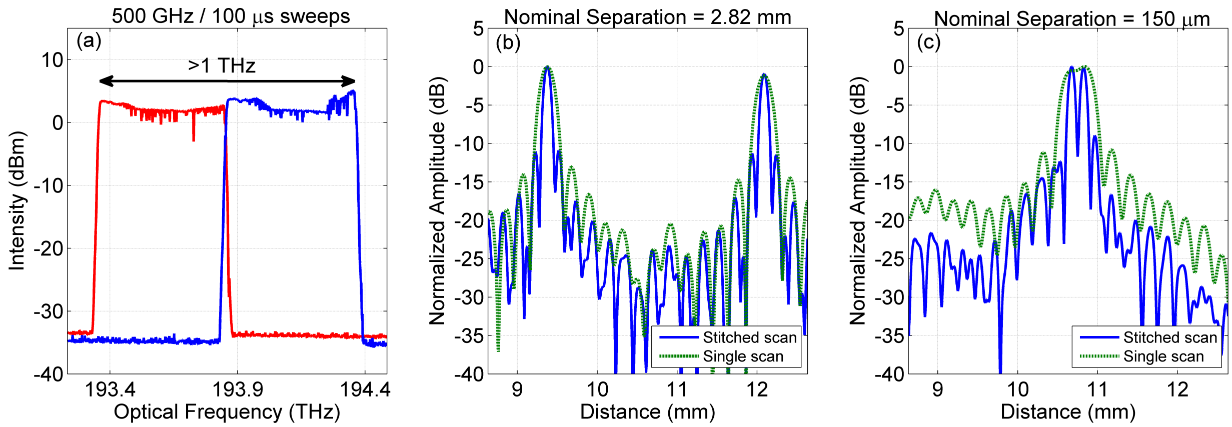

Fig. 2. Experimental results. (a) Optical spectra of individually chirped VCSELs. (b) Imaging of a 2.82 mm acrylic plate. (c) Imaging of a 150μm glass microscope coverslip.

a set of measurements performed over adjacent frequency bands, provided that the frequency as a function of time for each chirped waveform is known exactly. This requirement is partially satisfied by the use of an optoelectronic feedback scheme [6], in which a fiber Mach-Zehnder interferometer (MZI) is used to measure the chirp rate and lock it to a constant value. Feedback is applied to each VCSEL sequentially, and light from a particular device is selected through the use of an optomechanical switch. The resultant system, shown in the left part of Fig. 1, yields a perfectly linear frequency vs. time behavior that is repeatable from scan to scan. In addition to fixing the chirp rate, the feedback also sets the starting chirp frequency to an integer multiple of the MZI free spectral range (FSR). To fully satisfy the requirement for stitching, we add an external reference target to the imaging experiment, shown in the right part of Fig. 1, and follow the algorithm developed in [4] to extract the value of this integer. Therefore, the frequency as a function of time is known exactly, and a measurement with enhanced axial resolution can be synthesized.

Each VCSEL tunes 500 GHz in 100 μs, as shown in Fig. 2a, resulting in an effective bandwidth of 1 THz, and a corresponding free-space axial resolution of 150 μm. We demonstrate the improvement in the axial resolution by imaging thin slabs of transparent material. The processed data is shown in Fig. 2b, c. In Fig. 2b, the widths of the peaks due to the two slab facets are halved in the stitched scan vs. the single scan. In Fig. 2c, the two facets are not seen in the single scan. The improvement in axial resolution is directly verified by our ability to resolve the two targets in the stitched scan. The measurements are performed at a target distance of about a centimeter, which can be further increased. This result is a step towards realizing high-resolution imaging, e.g. optical coherence tomography, in a compact low-cost system with no moving parts.

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